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Design improvements and performance testing of a biomass gasifier based electric power generation system

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ABSTRACT

The objective of the research work, reported in this paper is, to design and develop a down draft gasifier based power generation system of 75 KW_e. A heat exchanger was designed and installed which recycles the waste heat of the hot gas, to improve the efficiency of the system. An improved ash removal system was introduced to minimize the charcoal removal rate from the reactor, to increase the gas production efficiency. A detailed analysis of the mass, energy and elemental balance is presented in the paper. The cold gas efficiency of the system is increased from 75.0% to 88.4%, due to the improvements made in the ash removal method. The Specific Fuel Consumption (SFC) rate of the system is 1.18 kg kWh^{-1}. The energy conversion efficiency of the system, from fuel wood to electric power was found to be 18%. Significant increase in calorific value of the producer gas was achieved by supplying hot air for gasification.

1. Introduction

Biomass gasifier based power generation system has a significant potential to replace fossil fuels and to reduce CO_2 emission. The World Energy Outlook highlights the need to reduce imports of oil and emission of CO_2, through sustainable use of biomass [1]. About 90% of the rural households in developing countries are dependent on biomass to meet their daily energy needs [2]. In South Asia alone about 42% of the global population have little or no access to electricity [3]. More than 70% of population in India is dependent on biomass to meet their primary energy needs [4]. The estimated potential of biomass generation in India is 800 million tonne per annum. The biomass available to use as a fuel source has a large potential to generate electricity in the order of 17,000 MW_e. At present, the installed capacity of the power plant is only 901 MW_e, which accounts for 5.3% of the total potential, through biomass [5]. According to the Ministry of Power (MoP), there are 89,808 villages are un-electrified, in India [6]. Biomass gasifier based power generation system is one of the suitable options that can be explored to enhance access to electricity to these villages.

In 2005, the “Ministry of New and Renewable Energy (MNRE)” launched a “Village Energy Security Program (VESP)”.

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Nomenclature

A_G total quantity of the sensible heat energy gained by input air, which is used for gasification of the fuel wood during the performance test (MJ)
A_j quantity of air fed for gasification of fuel wood at the jth hour (kg)
C total quantity of carbon element present in producer gas (kg)
C_p specific heat of the producer gas (kJ kg^{-1} K^{-1})
C_{vg} energy content of the producer gas (MJ Nm^{-3})
C_{vw} calorific value of the fuel wood used for gasification during the test period (MJ kg^{-1})
C_w total quantity of carbon present in the input material of air and fuel wood (kg)
D_c dust content of the producer gas estimated during the performance test (kg)
D_w total quantity of dust carried away by the producer gas (kg)
E_{CP} total quantity of heat loss during the gas cooling process through venture scrubbers (MJ)
E_G total energy content of the producer gas produced during the performance test (MJ)
E_{HX} total quantity of heat loss from the heat exchanger (MJ)
E_P total numbers of units of electricity produced during the performance test (kWh)
G_j quantity of producer gas produced at jth hour and m represents total number of hours of performance test period (j varies from 1 to 24-h)
G_L sensible heat energy carried away by the producer gas exits from heat exchanger (MJ)
G_v total volume of the producer gas produced, during the experiment (N m^3)
G_w the total weight of the producer gas produced during the performance test (kg)
H_2 total quantity of hydrogen element present in producer gas (kg)
H_{2w} total quantity of hydrogen present in the input material (air and fuel wood)
I_E total energy input to the gasifier (MJ)
I_{EL} total mass of the input of elements, contributed by fuel wood and air input (kg)
I_{HX} energy input (in the form of sensible heat) to the heat exchanger through the producer gas produced during the performance test (MJ)
I_m total quantity of input material by weight (kg)
m total number of hours of performance test period. Here m varies from 1 to 24 (number of hours).
MC moisture content of the fuel wood used for gasification during the test period (% by weight)
n total number of batches of fuel wood charging during the performance test period. Here n varies from 1 to 8 (8 number of batches of fuel wood charging)
N_2 total quantity of nitrogen element present in producer gas (kg)
N_{2w} total quantity of nitrogen in the input materials of air and fuel wood (kg)
O_2 total quantity of oxygen element present in producer gas (kg)
O_{2w} total quantity of oxygen in the input material of air and fuel wood (kg)
O_E total energy output from the gasifier during the performance test (MJ)
O_m total weight of the output products, obtained by gasification of fuel wood (kg)
p percentage of nitrogen content in producer gas (% by weight)
q percentage of carbon monoxide content in producer gas (% by weight)
r percentage of carbon dioxide content in producer gas (% by weight)
R_w total quantity of ash collected from the ash pit, after the 24-h performance test (kg)
s percentage of methane content in producer gas (% by weight)
t percentage of hydrogen content in producer gas (% by weight)
T_1 temperature of the producer gas at the inlet of the heat exchanger (°C)
T_2 temperature of the producer gas at the outlet of the heat exchanger (°C)
T_3 temperature of the gas at the inlet of the paper filter (°C)
U_E quantity of unaccounted elements in elemental balance analysis (kg)
U_L unaccounted component of the energy balance analysis. U_L includes heat loss in gasifier and ash pit, which are not reflected in the energy balance analysis (MJ)
U_w unaccounted component of the mass balance analysis. U_w includes dust and un-estimated fine particles carried away by the gas. The unaccounted component include suspended dust particle in ash pit water seal (kg)
W_A total weight of the air fed for gasification of fuel wood during the testing period (kg)
W_i weight of the fuel wood charged in ith batch (kg)
W_w total weight of the fuel wood, charged during the entire period of the test run (kg)
$x_{O_{2w}}$ percentage of oxygen content in input air used for gasification of fuel wood (% by weight)
$y_{N_{2w}}$ percentage of nitrogen content in input air used for gasification of fuel wood (% by weight)

Greek letters

α_{C_w} percentage of carbon content in fuel wood (% by weight),
$\beta_{H_{2w}}$ percentage of hydrogen content in fuel wood (% by weight)
$\delta_{N_{2w}}$ percentage of nitrogen content in fuel wood (% by weight)
η_{BP} conversion efficiency of the system from biomass to electricity (%)

η_G	conversion efficiency of the system from biomass to producer gas (%)	ρ	density of producer gas per (kg Nm^{-3})
η_{GE}	conversion efficiency of the gasifier system, from producer gas to electricity (%)	$\omega_{O_{2w}}$	percentage of oxygen content in fuel wood (% by weight)

This program was aimed to address the total energy need of the remote villages, through biomass resources. An installed capacity of 700 kW_e was achieved through this program, to electrify 36 villages. Out of 700 kW_e, 90% of the electricity is produced through the biomass gasifier based power plants. Thirty-six gasifier based power plants were installed as a part of this program. Among the 36 biomass gasifier based power plants, 31 systems are functioning [7]. Though the exact number of operating gasifier power plants (in India) is not known, the report [7] indicates that 75% of the plants installed after 2005, are functional. Some of the plants are non-functional due to technical and operational issues. The installed capacity of the gasifier based power plants in India was reached to 80 MW_e, during the period from 1992 to 2006 [8].

To realize the maximum available potential of biomass resources for power generation, there is an urgent need to make improvement in the state of art of the technology pertaining to biomass conversion systems. The objective of the present research work is to improve the performance of the biomass gasifier system for power generation. The gasifier used in the present study is having a down draft type reactor.

The key factors influencing the performance of the gasifier based power generation system were identified and improved. The parameters considered for improving the performance efficiency of the gasifier system are:

I. Optimization of fuel to air ratio, which is known as Equivalence Ratio, (ER). ER is the ratio of air supplied for gasification to the stoichiometric air required for complete combustion of the fuel.
II. Optimization of charcoal return rate, from the gasification reactor to the ash pit. The higher the charcoal return rate into the ash pit indicates the lower conversion efficiency of the biomass into gas.
III. Waste heat recovery from the hot gas and supply of hot air to the reactor, to minimize the heat loss and to improve the efficiency of the system.

Inline with the above said objectives, the charcoal return rate was minimized by improving the ash removal mechanism. Minimizing the charcoal return rate from the reactor increases the fuel wood to producer gas conversion rate and contributes to increase the cold gas efficiency. Heat loss from the reactor zone was minimized by creating multilayer, high temperature insulation. Waste heat carried away by the hot gas was minimized by the introduction of an efficient heat recovery system. The heat recovery system recycles the sensible heat energy from the hot gas to the gasifier by supplying preheated air for gasification process.

Gasification efficiency and ER are interrelated. Higher the ER, higher will be the nitrogen content in the gas. Reduction in ER will result in reduced air supply, leading to higher amounts of charcoal return from the reactor. Both these scenarios shall result in reduction of cold gas efficiency of a biomass gasifier. Hence, there is a need to optimize the ER to achieve maximum cold gas efficiency. The influence of ER on cold gas efficiency is discussed [9–12], where cold gas efficiency of 69.2% was achieved with an ER of 0.21. The cold gas efficiency variation in the ER, from 0.2 to 0.4 was reported [13,14].

In the present study, a detailed mass balance, energy balance and elemental balance of a biomass gasifier based power generation system was carried out. The mass balance analysis was conducted to estimate and understand the mass flow of the input material and output products across the system. The mass flow analysis also indicates the consistency of the test results related to conversion efficiency of biomass into producer gas. It was used as a tool to optimize the charcoal return from the reactor and ER. Similarly energy balance analysis was used as a tool to study the energy flow within the system and to optimize the efficiency. The outcome of the elemental balance is an indicator to verify the results of the mass balance and energy balance. There are very few publications available on the mass and energy balance analysis of biomass gasifier [10,14,15]. The mass balance and energy balance analysis of a counter current fixed bed gasifier is reported [10]. It compares the performance of a wood-based gasifier system with that of a Refuse Derived Fuel (RDF) based on various parameters. Analysis of mass balance and energy balance was reported by Chern et al. [15]. However, these studies [10,14,15] have not reported elemental balance analysis.

Overall improvement in the efficiency of the system was compared before and after modifications. The results were also compared with the published research work, with respect to the parameters considered for improvement of the system performance.

2. Description of the biomass based power generating system

The biomass gasifier based power generation system has a fixed bed down draft reactor, a heat exchanger for hot air generation and a series of gas cleaning and cooling equipment. The reactor was designed with multilayer insulation, to reduce the heat loss and to maintain high temperature. Hot air was injected into the gasification reactor through twelve nozzles, distributed equally at two tiers. Six nozzles were provided in each tier.

A vibrating grate, ash removal system was introduced to remove the ash from the reactor, at a regular interval. The vibrating grate was designed in such a way, that it removes only the ash from the reactor while retaining the charcoal in

the reactor. Minimizing the charcoal removal rate increases the biomass to gas conversion efficiency.

Since, the reactor is a down draft type, producer gas is drawn through the grate and the gas exit from the bottom of the gasifier. A cyclone filter was introduced immediately after the outlet of the gasifier, to remove the coarse dust. After removal of coarse dust through cyclone filter, the hot gas was passed through a shell and tube type heat exchanger. Air passes through the shell whereas the gas was passed through the tubes. The ambient air was preheated to 250 °C using the sensible heat energy available from the hot gas. The gas was cooled and cleaned by two Venturi scrubbers, connected in series. The gas was further cooled down to 18 °C by using a gas cooler. The reduction in the producer gas temperature allows condensation of the moisture present in the gas. The condensate was collected in a sump. The producer gas was finally passed through a fabric filter and a paper filter, connected in series to remove the fine dust particulates. The clean producer gas was used to drive an Internal Combustion (IC) engine for generating electric power. The gasifier is designed to perform with high efficiency and to produce cleaner gas, with less impurities. The components of the biomass gasifier based power generation system are shown in Fig. 1. Design criteria considered for the gasifier, heat exchanger and ash removal system are presented in Table 1. A manufacturer, who is the licensee of the institute, fabricated the gasifier system. The gasifier system has been installed and working at the research facility.

2.1. Reactor component of the biomass gasifier

The down draft type gasification reactor was designed for conversion of biomass into combustible gas known as "producer gas". The complete gasifier system was fabricated using mild steel with the sheet thickness of 4 mm. The reactor was designed with a low Specific Gasification Rate (SGR) to ensure free flow of large size fuel in the reactor. Multiple layers of insulation linings were used to minimize the heat loss and maintain a high temperature inside the reactor.

A fuel hopper was designed to store the fuel for a continuous operation of five hours. The gasifier was operated in force draft mode with a pressure between 30 cm and 40 cm of water column. A lid with water seal arrangement has been provided at the top of the gasifier for fuel feeding. The lower part of the gasifier is provided with a water seal arrangement to facilitate continuous removal of ash from the reactor.

2.2. Hot air generation using the sensible heat from the hot gas

The sensible heat of the hot gas was used to preheat the air; otherwise, this energy is wasted in the cooling process. A heat exchanger has been designed to preheat the air used for gasification of the fuel wood. At the entry of the heat exchanger, the gas flows upward at a low velocity, which enables the separation of heavy particulates due to gravity. The producer gas generated from the reactor is drawn from the high temperature zone, maintained around 1000 °C. At the exit of the gasifier the temperature of the hot gas is in the range of 500 °C–600 °C. The sensible heat carried away by the hot gas accounts for 8–10% of the total input energy. The hot gas and the air were passed through a shell and tube heat exchanger. The ambient air was heated to 250 °C by using the sensible heat of the hot has. In the heat exchanger gas is cooled down to 300 °C by transferring the sensible heat energy to the ambient air. A diagram of the heat exchanger is shown in Fig. 2. The dimensions provided in the figure are in millimeter. Supply of the hot air for gasification enhances the tar cracking

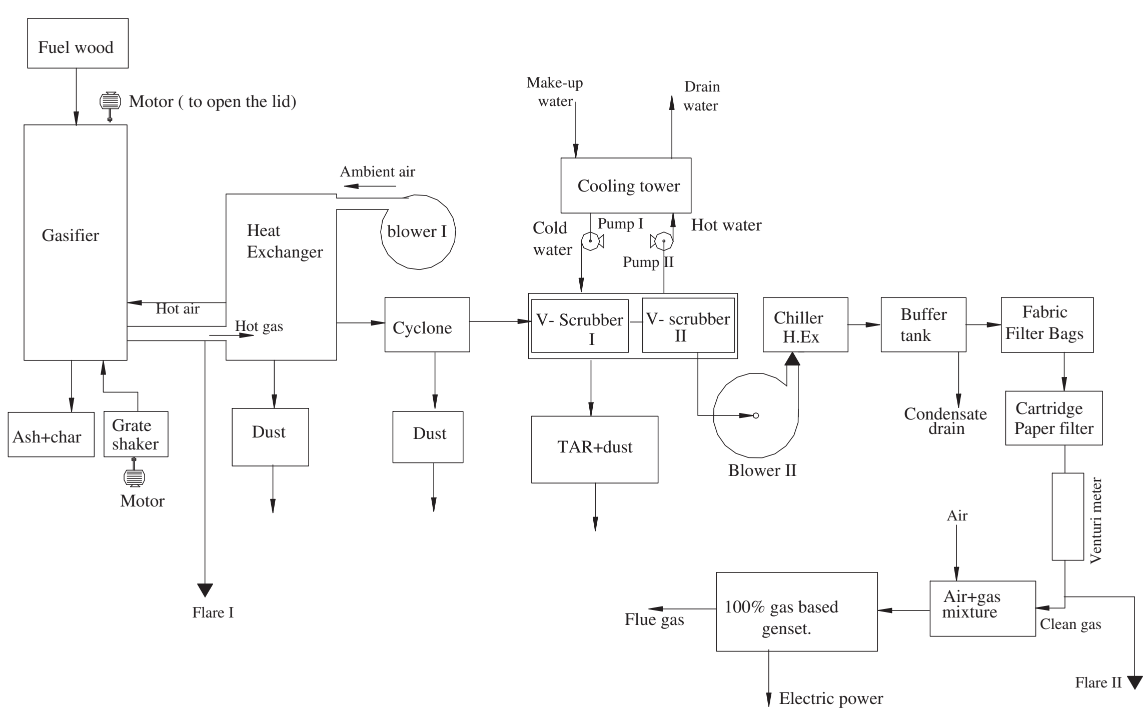

Fig. 1 – A block diagram of the biomass gasifier based power generation system.

Table 1 – The design criteria for gasifier, heat exchanger and ash removal system.

Component	Parameter	Design specification
Biomass gasifier	Power output	75 kW_e
	Specific Gasification Rate (SGR)	0.2 $Nm^3\ cm^2\ h^{-1}$
	Air velocity at nozzles	15 $m\ s^{-1}$
	Reactor temperature	>1000 °C
	Gas temperature at the exit of gasifier	>600 °C
	Hot air supply for gasification	>200 °C
	Tar level in raw gas	<300 mg Nm^{-3}
	Tar level in clean gas	<50 mg Nm^{-3}
	Fuel storage capacity of the hopper	600 kg
Heat exchanger	Gas temperature at the inlet	>500 °C
	Gas temperature at the outlet	<100 °C
	Air temperature at the inlet	30 °C
	Air temperature at the outlet	<100 °C
	Tube bank arrangement	In line
	Number of passes	Three
	Flow direction of air and gas	Counter flow
Ash removal system	Vibrator motor specification	Single phase, 220 V AC. 0.5 Hp. 1500 RPM
	Vibration transmission	Sealed rotating cable transmitter
	Vibrating duration	20 s
	Vibrating frequency	At every 20 min
	Vibration control	Single phase timer switch
	Ash + char removal rate	<1% of the weight of feed material

process in the reactor. Cracking of tar improves the quality of the producer gas and reduces the load on the gas cleaning equipment. Recycling the sensible heat energy of the hot gas into the reactor by supplying the hot air improves the gas quality as well as the overall efficiency of the system.

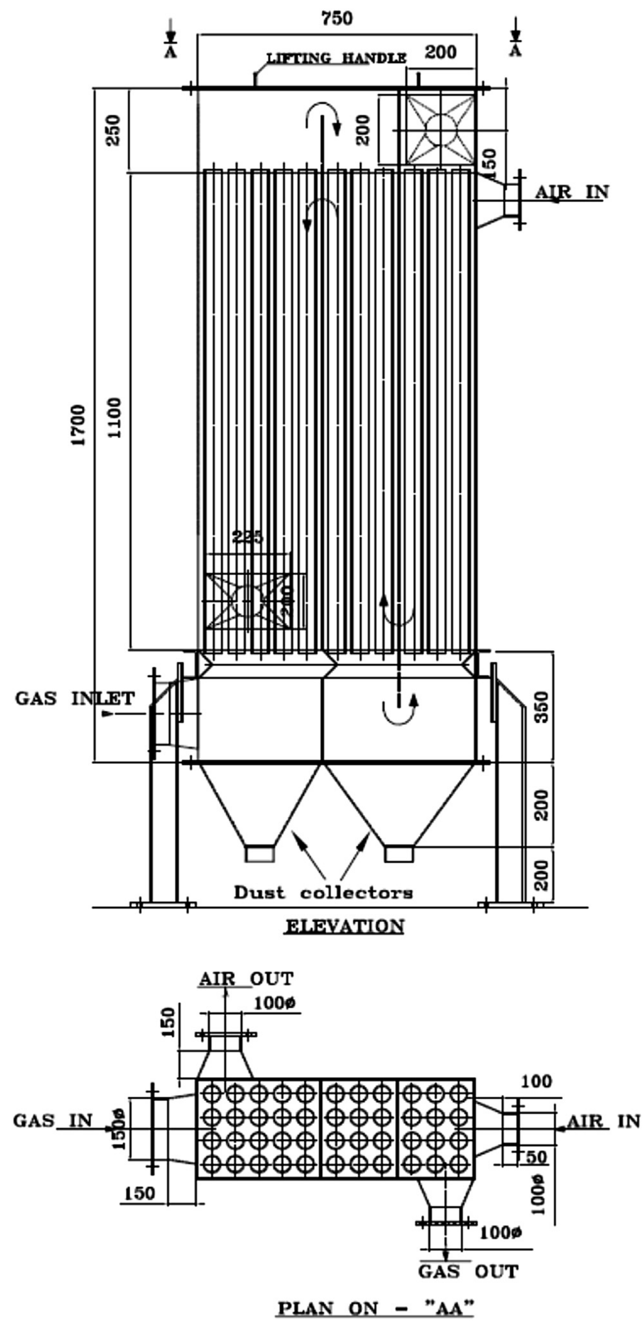

Fig. 2 – Details of the heat exchanger with components.

2.3. *Vibrating grate ash removal system*

An improved ash removal system was designed to minimize the charcoal falling from the reactor, into the ash pit. A vibrating grate mechanism was introduced to remove the ash from the reactor, at a regular interval. It consists of an ash removal grate, an electric motor coupled with a vibrator, and a vibration transmitter. The duration of the vibration and frequency of operation of the grate can be varied depending upon the fuel type and operating load of the gasifier. A timer switch has been introduced for effective removal of the ash from the reactor. The timer switch has been programmed in such a way to activate the vibrator at desired intervals. This ash removal system allows only the dust particles and ash to pass through the grate and avoids falling of charcoal from the reactor. By minimizing the amount of charcoal, falling out from the reactor, the vibrating grate ash removal system improves the gas production efficiency of the reactor. A diagram of the gasifier with the details of the reactor and vibrating grate ash removal system are shown in Fig. 3. The dimensions provided in the figure are in millimeter.

2.4. *Gas cooling and cleaning system*

The gas from the heat exchanger is further cleaned and cooled in two venturi scrubbers, connected in series. The gas enters the wet scrubbers from the bottom and moves upwards. In the

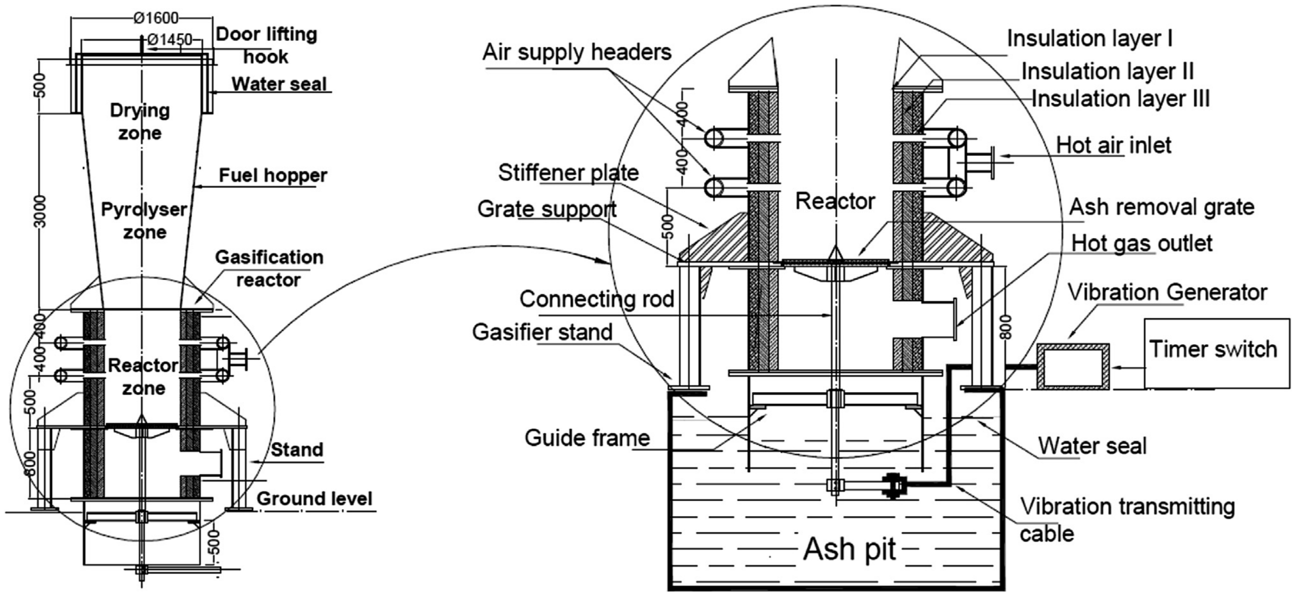

Fig. 3 – Details of the gasifier and the reactor with vibrating grate ash removal system.

venturi scrubber, water is sprayed from the top, which removes the tar and dust from the gas. When the water spray washes away, the impurities present in the producer gas the clean gas flows upward towards the outlet. The throat of the venturi scrubber provides adequate contact between gas and water for an efficient gas cleaning. The water coming out from both of the venturi scrubbers was cooled using an evaporative cooling tower. Rotameters are connected to the water inlet of both the venturi scrubbers monitoring of the water flow rate. The gasifier system with wet scrubbers produces wastewater, which needs pre-treatment before disposal. The wastewater quality can vary with the gas quality, particularly with the tar content and its nature. A detailed study was undertaken for analysis and optimization of the wastewater treatment process [16].

2.5. *Online gas cooler*

The gas exit from the scrubber is saturated with water vapor, which needs to be removed before the gas is allowed to pass through the fabric filter. The moisture may clog the fabric filter, which will increase the pressure drop and will affect the system performance. A gas cooler was used to cool the gas and condensate the vapor to separate the moisture. The gas cooler is a shell and tube type heat exchanger. The gas passes through the shell and the cooling refrigerant passes through the tube. The gas enters the cooler at a temperature ranging from 20 °C to 28 °C and exits at a temperature ranging from 10 °C to 18 °C. Reducing the gas temperature by 10 °C helps to condense and remove the moisture in the gas, before it reaches the fabric filter.

2.6. *Electric power generator using 100% producer gas engine*

An internal combustion (IC) engine, having six cylinders, with 140 mm bore and 152 mm stroke was used to operate on producer gas. The engine is water-cooled type coupled with a radiator and a fan. An electrical load bank consisting of air heaters was designed to have a heating load of up to 75 KW_e. Current Transformer (CT) coils were installed to monitor the current in each phase. A three-phase energy meter was used to monitor the electricity generated by the system.

3. Methodology adopted for performance test

The performance of the gasifier system was evaluated by studying different technical parameters. The parameters considered for this study were analyzed and compared with

Table 2 – Parameters identified for performance monitoring.

No.	Component	Parameter monitored
1	Mass balance	Fuel consumption rate Ash return and dust content Air flow rate Gas flow rate
2	Energy balance	Quantity and calorific value of fuel Quantity and calorific value of producer gas
3	Elemental balance	Ultimate and proximate analysis of fuel Gas analysis
4	Temperature measurement	Gas temperature at various points Air temperature at various points
5	Pressure drop measurements	Pressure drop across various components
6	Electrical output	Hourly electricity generation

the results obtained before and after the design improvements. The mass balance, energy balance and elemental balance of the system was carried out. The quality of the electric power output was monitored throughout the experiment. The efficiency of the gasifier system was estimated based on the biomass consumption and electricity generation. A summary of the technical parameters monitored to evaluate the performance of the system is presented in Table 2.

3.1. Experimental conditions

The experiment was conducted by operating the gasifier system continuously for a period of 24 h. The temperature of the air and gas were monitored at various locations of the heat exchanger. The fuel wood consumption was monitored at every hour. The gasifier can accept fuel wood up to 15% moisture content, to produce a good quality gas. The moisture content of the fuel has a strong influence on the gas quality. Variation in the gas quality with the moisture content of the fuel wood was reported in Ref. [17]. For the purpose of the experiment, the fuel wood from a same lot was used to minimize the variation, in terms of its moisture content, calorific value etc. Gas flow rate, air flow rate and power output were also monitored at every hour. The experimental conditions are presented in Table 3.

3.2. Preparation of the system for performance study

The fuel hopper, reactor, and ash pit were completely emptied to remove any residual fuel and ash to ensure accuracy in mass balance analysis. The dust collectors at the cyclone filter and heat exchanger were cleaned to ensure the accuracy in the estimation of the dust content in the gas. Before commencing the experiment water sumps were replaced with fresh water, fabric filter and paper filter were replaced with fresh filters. The performance testing was started by igniting the fuel wood in the reactor, through the air supply nozzles, using a kerosene torch. The gas flaring valve was kept in the open position and the gasifier system was allowed to run for two hours forty-five minutes to reach the steady state condition. This quantum of time, which is required to heat up the gasification reactor to the desired temperature from the cold start conditions. Hot air, which is generated by using the sensible heat energy from the hot gas, was injected into the reactor for gasification of fuel wood. The gas was diverted to run the engine, when the gas temperature was at 570 °C and the air temperature was at 250 °C at the heat exchanger.

3.3. Instruments and their accuracy

A digital pressure difference monitor (PDM) was used to measure the pressure drop across various components of the gasifier system. A duly calibrated hot wire anemometer was used to measure the air flow rate. The gas flow rate was measured using a Venturi meter, installed before the inlet to the engine. Details of the equipment used during the experiment are provided, with their accuracy and error level, in Table 4. It may be noted from Table 4, the maximum error level of the instruments used for the mass flow and energy flow analysis is in the range of ±1%. The gas chromatograph is calibrated using a sample of gas drawn from canisters with known gas composition. Flow meters were calibrated from accredited laboratories. The uncertainty in the results due to inaccuracy of the instruments could be in the range of ±1%.

4. Mass balance

The biomass gasifier, gas cleaning equipment, gas cooling equipment and the engine are considered as a single system for this analysis. The mass balance analysis was carried out by estimating the mass flow of the materials across the system boundary. This includes balancing of different input materials such as fuel wood and air and output materials such as producer gas, ash and tar.

Table 3 – Details of experimental conditions.

No.	Component	Experimental conditions
1	Fuel size	The fuel size not to exceed 75 mm × 75 mm × 75 mm and not less than 60 mm × 60 mm × 60 mm
2	Property of the fuel wood	Fuel wood from a same lot is used to avoid any variation in fuel property. A sample of the fuel wood is used for ultimate and proximate analysis.
3	Fuel wood consumption rate	A reference level is marked 10 cm bellow the top level of the fuel hopper. Fuel wood is charged at every hour till the level marked.
4	Gas temperature	Gas temperature at exit of the gasifier to be above 400 °C and 35 ± 5 °C at the inlet of the engine manifold.
5	Initial flaring of the gas	At the time of initial ignition, the gas to be flared for two hours, to ensure the quality of the gas suitable to run the engine.
6	Hot air temperature	Temperature of the hot air supplied to be above 200 °C, for ensuring quality of the gas.
7	Power output	Operating the system in the range of 70 ± 5 kW_e load
8	The ash removal system	The ash removal grate vibrator is to be on for a duration of 20 s at every 20-min intervals
9	Water temperature at the inlet of the venturi scrubber	Water temperature, at the inlet of the venturi scrubbers to be in the range of 35 ± 10°

Table 4 – Details of the equipment used during the experiment.

No.	Instrument	Measurement	Least count	Error level
1	Hot wire anemometer	Air flow measurement	0.1 m/s	±1%
2	Pressure differential meter (PDM)	Pressure drop	0.1 mm	±0.2%
3	Digital temperature indicator	Temperature measurements	0.1 °C	±1%
4	Weighing balance	Fuel feeding rate	100 g	±20 g
5	Rotameter	Water flow rate (to venturi scrubbers)	5 L min^{-1}	±1.0%
6	Voltmeter	Monitoring the voltage output	1 V	±0.5%
7	Wattmeter	Monitoring the power output	1 W	±0.5%
8	Frequency meter	Monitoring the frequency	0.1 Hz	±0.2%
9	Energy meter	Monitoring the energy output	1 kWh	±0.5%
10	Gas Chromatograph	Gas component analysis	0.01%	±1%

The gasifier can be operated by using the fuel wood with a minimum size of 20 mm × 20 mm × 20 mm to a maximum size of 100 mm × 100 mm × 100 mm. During the experiment, the gasifier was operated with the fuel wood size ranging from 60 mm × 60 mm × 60 mm to 75 mm × 75 mm × 75 mm. The feed rate of the fuel wood was continuously monitored throughout the experiment. The quantity of the fuel wood fed into the gasifier was estimated at each batch. While starting the experiment, the gasifier hopper was filled with fuel wood up to 5 cm below the top edge of the hopper. The level of fuel wood when starting the gasifier was treated as the reference level for each fuel feeding, thorough out the experiment. Fuel wood was charged every two hours up to the reference level and the weight of the biomass intake was monitored. To ensure continuous operation of the system, fuel wood was charged without switching off the generator set by operating it in suction mode. The mass balance of the system is done by balancing the total weight of the input material and the output material.

The total weight of the input i.e. fuel wood and air fed into the gasifier was estimated using Eq. (1).

$$I_m = W_w + A_w \tag{1}$$

The total weight of the fuel wood (W_w) charged during the entire period of the performance test was estimated using Eq. (2).

$$W_w = \sum_{i=1}^{n} W_i \tag{2}$$

The total weight of air fed for gasification of fuel wood during the entire period of the performance test was estimated using Eq. (3).

$$A_w = \sum_{j=1}^{m} A_j \tag{3}$$

The total weight of the output products (O_m) obtained from the gasification of fuel wood was estimated using Eq. (4).

$$O_m = G_w + R_w + D_w + U_w \tag{4}$$

The total weight of the producer gas (G_w) produced during the performance test was obtained using Eq. (5).

$$G_w = \sum_{j=1}^{m} G_j \tag{5}$$

Total quantity of the dust (D_w), carried away by the producer gas was estimated using Eq. (6).

$$D_w = D_c \times G_w \tag{6}$$

The unaccounted component of the mass balance analysis, 'U_w' is estimated using Eq. (7).

$$U_w = I_m - (G_w + R_w + D_w) \tag{7}$$

5. Energy balance

The energy balance analysis was carried out by estimating the energy content of the input and output materials. Fuel wood samples were collected from each lot of fuel wood fed into the gasifier during the experiment. Proximate analysis of the fuel wood samples was carried out to find out ash content and moisture content. The ultimate analysis of the fuel wood samples was carried out to find out Carbon, Hydrogen, Oxygen and Nitrogen content. The energy input to the system was estimated based on total fuel wood consumption and its calorific value.

The gas samples were collected and analyzed using a gas chromatograph, to obtain the gas components of the producer gas. The calorific value of the producer gas is estimated based on the combustible gas components of the producer gas. The composition of the producer gas is obtained by analyzing the gas through a gas chromatograph. The results of the gas analysis are presented in Table 5. It may be noted from Table 5, carbon monoxide contributes 21% of the producer gas. The hydrogen content of the producer gas is 23% and methane content of the producer gas is less than one percent. The nitrogen content of the producer gas is estimated by difference.

Table 5 – Composition of producer gas (volume fraction percentage).

No.	Gas component	Percentage by volume
1	Carbon monoxide (CO)	21.0
2	Carbon dioxide (CO_2)	9.5
3	Hydrogen (H_2)	23.0
4	Methane (CH_4)	0.9
5	Nitrogen (N_2)	45.6

The total energy output of the system was calculated using the gas flow rate and calorific value of the producer gas. The amount of the energy recycled into the reactor and the heat loss are estimated by measuring the temperature of air and gas, at the inlet and the outlet of the heat exchanger.

5.1. Estimation of the Input energy

Total energy input to the gasifier 'I_E' was estimated using Eq. (8).

$$I_E = W_w \times C_{vw} \times \left\{\frac{(100 - MC)}{100}\right\} \tag{8}$$

5.2. Estimation of the output energy

Total energy output, 'O_E' from the gasifier was estimated using Eq. (9).

$$O_E = E_G + E_{Hx} + E_{CP} + U_L \tag{9}$$

The total energy content of the producer gas (E_G) produced during the performance test is estimated using Eq. (10).

$$E_G = \sum_{j=1}^{m} G_j \times C_{vg} \tag{10}$$

Total quantity of the heat loss from the heat exchanger was estimated using Eq. (11).

$$E_{HX} = I_{HX} - (A_G + G_L) \tag{11}$$

The sensible heat energy input (I_{HX}) from the producer gas to the heat exchanger was estimated using Eq. (12).

$$I_{HX} = G_v \times \rho \times C_p \times (T_1 - T_2) \tag{12}$$

The total quantity of the heat loss (E_{CP}) due to the gas cooling process through venturi scrubbers was estimated using Eq. (13).

$$E_{CP} = G_v \times \rho \times C_p \times (T_2 - T_3) \tag{13}$$

Unaccounted component 'U_L' of the energy balance analysis was estimated using Eq. (14).

$$U_L = I_E - (E_G + E_{HX} + E_{CP}) \tag{14}$$

6. Elemental balance

A detailed elemental balance analysis of the input materials and the output products was carried out for evaluating the performance of the gasifier system. Elemental balance analysis had been carried out by estimating the individual elements present in the input materials and the output products. The results of the ultimate analysis of the fuel wood and analysis of the gas components of the producer gas are used to estimate the elemental balance.

The elemental contribution of the fuel wood and air is estimated by using the three steps, as given below.

i) Estimation of the total weight of the fuel wood fed into the gasifier and total quantity of air fed for gasification of the fuel wood.
ii) Estimation of the individual element and their individual weight contributed from the input material i.e. fuel wood and air.
iii) Estimation of the individual element's mass contribution by adding the identical elements present in the fuel wood and air.

The elemental contribution of the producer gas is estimated by using the two steps as given below.

i. Estimation of the individual gas components of the producer gas.
ii. Estimation of the individual element's mass contribution by adding the identical elements present in various components of the producer gas.

Individual elements of the input material I_{EL1} were estimated using Eq. (15).

$$I_{EL1} = W_w(\alpha_{Cw} + \beta_{H_{2w}} + \omega_{O_{2w}} + \delta_{N_{2w}}) + W_A\left(x_{O_{2w}} + y_{N_{2w}}\right) \tag{15}$$

Eq. (5), used for estimation of the input element can be written as Eq. (16).

$$\begin{aligned} I_{EL} = {} & (W_w \times \alpha_{Cw})_{C_w} + \left(W_w \times \beta_{H_{2w}}\right)_{H_{2w}} \\ & + \left[(W_w \times \omega_{O_{2w}}) + (W_A \times x_{O_{2w}})\right]_{O_{2w}} \\ & + \left[(W_w \times \delta_{N_{2w}}) + (W_A \times x_{O_{2w}})\right]_{N_{2w}} \end{aligned} \tag{16}$$

The individual elemental contribution of different elements was estimated using Eqs. (17)–(20).

$$C_w = W_w \times \alpha \tag{17}$$

$$H_{2w} = W_w \times \beta \tag{18}$$

$$O_{2w} = \{(W_w \times \omega) + (W_A \times x)\} \tag{19}$$

$$N_{2w} = \{(W_w \times \delta) + (W_A \times y)\} \tag{20}$$

The total quantity of the individual elements present in the producer gas was estimated using Eq. (21).

$$\begin{aligned} O_{EL1} = {} & (p \times G_w)_{N_2} + (q \times G_w)_{CO} + (r \times G_w)_{CO_2} + (s \times G_w)_{CH_4} \\ & + (t \times G_w)_{H_2} + U_E \end{aligned} \tag{21}$$

Unaccounted component of the elemental balance analysis was estimated using Eq. (22).

$$\begin{aligned} U_E = I_{EL} - {} & (p \times G_w)_{N_2} + (q \times G_w)_{CO} + (r \times G_w)_{CO_2} + (s \times G_w)_{CH_4} \\ & + (t \times G_w)_{H_2} \end{aligned} \tag{22}$$

Total elemental contribution (O_{EL}) of the producer gas was estimated using Eq. (23).

$$\begin{aligned} O_{EL} = {} & (p \times G_w)_{N_2} + \{q \times G_w \times (12/28)\}_C \\ & + \{q \times G_w \times (16/28) \times (1/2)\}_{O_2} + \{r \times G_w \times (32/44)\}_{O_2} \\ & + \{r \times G_w \times (12/44)\}_C + \{s \times G_w \times (12/16)\}_C \\ & + \{s \times G_w \times (4/16)\}_{H_2} + (t \times G_w)_{H_2} + U_E \end{aligned} \tag{23}$$

Total quantity of carbon element (C) present in the producer gas was estimated using Eq. (24).

$$C = \{q \times G_w \times (12/28)\} + \{r \times G_w \times (12/44)\} + \{s \times G_w \times (12/16)\} \quad (24)$$

Eq. (24) used to estimate the carbon element "C" can be further written as Eq. (25).

$$C = G_w[\{q \times (3/7)\} + \{r \times (3/11)\} + \{s \times (3/4)\}] \quad (25)$$

Total quantity of the oxygen element (O_2) present in the producer gas can be estimated using Eq. (26).

$$O_2 = \{q \times G_w \times (16/28) \times (1/2)\} + \{r \times G_w \times (32/44)\} \quad (26)$$

Eq. (26) used to estimate (O_2), can be further written as Eq. (27).

$$O_2 = G_w \times [\{q \times (2/7)\} + \{r \times (8/11)\}] \quad (27)$$

The total quantity of the hydrogen element (H_2) present in the producer gas was estimated using Eq. (28).

$$H_2 = G_w \{s \times (1/4)\} + (t \times G_w) \quad (28)$$

Eq. (28) used to estimate the total quantity of the hydrogen element (H_2), can be further written as Eq. (29).

$$H_2 = G_w[\{s \times (1/4)\} + t] \quad (29)$$

The total quantity of the nitrogen element (N_2) present in the producer gas was obtained using Eq. (30).

$$N_2 = p \times G_w \quad (30)$$

7. Determination of the performance efficiency of the system

The performance efficiency of the biomass gasifier based power generation system was estimated in three steps as given below.

Step-1:Biomass to producer gas conversion efficiency of the system

In step-1, the performance efficiency of the gasifier system was estimated based on the biomass to gas conversion efficiency. The gas conversion efficiency referred here is the conversion efficiency of the energy content of biomass into the energy content of the cold gas. Biomass to producer gas conversion efficiency was estimated using Eq. (31).

$$\eta_G = \{E_G/I_E\} \times 100 \quad (31)$$

Step-2:Biomass to electrical power conversion efficiency of the system

The biomass to the electrical power conversion efficiency of the system η_{BP} was estimated using Eq. (32).

$$\eta_{BP} = \{(E_P \times 860)/I_E\} \times 100 \quad (32)$$

Step-3: Producer gas to electricity conversion efficiency of the 100% producer gas engine

In step-3, the efficiency of the engine was estimated based on the total electrical energy output and the total energy input of the producer gas, as given in Eq. (33).

$$\eta_{GE} = \{(E_P \times 860)/E_G\} \times 100 \quad (33)$$

8. Temperature measurements

In order to estimate the energy balance the gas and air temperature was monitored at several locations in the system as shown in Fig. 4.The gas and the air temperature was monitored regularly throughout the experiment at an interval of one hour. The temperature of producer gas and air measured at various locations of the heat exchanger are presented in Table 6.

9. Pressure drop measurements

Pressure drop was measured at various locations to monitor the performance of the system. The pressure drop across the gas cleaning filters is the key indicators of the gas quality and reliability of the system. Monitoring of the pressure drop also provides input, to plan the maintenance cycle of the gas cleaning equipment. A profile of the pressure drop across the fabric filter and the paper filter is shown in Fig. 5.

10. Monitoring the electrical output

The electrical output of the biomass gasifier based power generation system was monitored throughout the period of the test run. The performance of the generator with the summary of the electrical power output is presented in Table 7. A profile of the electrical power output along with time is shown in Fig. 6.

10.1. *Power output*

During the experiments, the power output rate was remained within the range of 65 kW_e–71 kW_e. Variation in frequency is observed from 46.6 to 53.6 Hz (Table 7). The frequency of the generator was controlled by controlling the speed of the

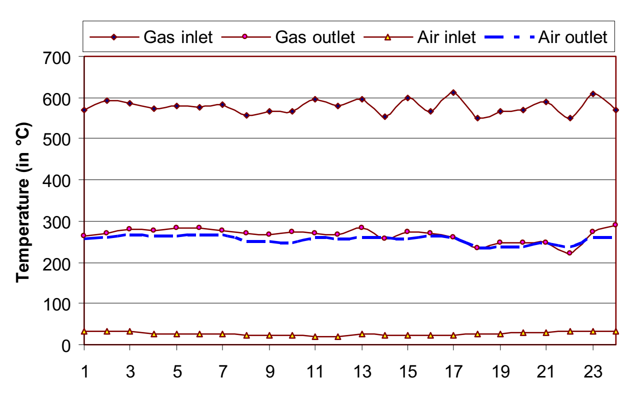

Fig. 4 – Temperature profile of air and gas.

Table 6 – Temperature measurements across the heat exchanger.

Time	Heat exchanger			
	Gas inlet (°C)	Gas outlet (°C)	Air inlet (°C)	Air outlet (°C)
1	570	264	34	256
2	593	270	34	261
3	586	281	32	268
4	573	276	27	264
5	580	282	27	264
6	577	282	27	267
7	584	277	26	266
8	556	269	24	252
9	567	268	24	252
10	565	274	24	249
11	596	269	21	261
12	580	267	20	256
13	595	283	25	260
14	552	258	23	261
15	598	272	23	257
16	566	269	24	263
17	611	260	24	262
18	549	236	27	233
19	566	247	26	239
20	570	247	28	239
21	590	246	28	246
22	551	221	31	238
23	610	273	32	260
24	569	291	33	262

engine. A hydraulic governor is used for sensing the variation in the RPM (Revolution Per Minute), which occurs due to the variation in load. The hydraulic governor controls the throttle valve to maintain the RPM closer to 1500 to keep the frequency in the range of 48 Hz–52 Hz. The hydraulic governor was designed to operate the natural gas engine, is not performing up to the mark with the producer gas. Some time, manual adjustment of the throttle valve was needed to correct the frequency of the power output. The frequency reported in Table 7, was observed during the long duration performance test and without manual adjustment of the throttle valve. The power output at variable load conditions along with gas flow rate, fuel wood consumption and frequency are presented in Table 8. It may be noted from Table 8, when the load was varied from 5 kW_e to 73 kW_e, the frequency was varied from 49.2 Hz to 51.8 Hz. The variation in frequency was minimized by manual adjustment of the throttle valve. To minimize the variation in the frequency, in most of the producer gas engines the fuel mixture intake is controlled by manual adjustment of valves [18]. Need of the manual adjustment of governor in 100% producer gas engines is reported by Mazumdar [19].

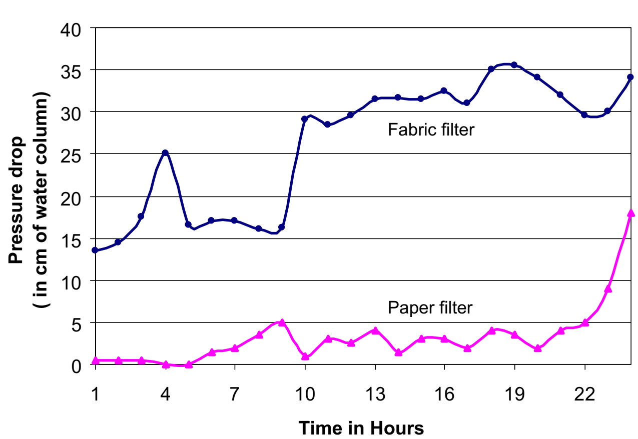

Fig. 5 – Pressure drop across the fabric filter and paper filter.

11. Results and discussions

Performance analysis of the gasifier based power generation system was carried out to analyze the mass, energy and elemental balance of the input materials and output products. The overall performance analysis of the system and the results obtained are discussed in the following chapters.

11.1. *Design optimization of the gasification reactor*

Air distribution in the reactor is a key influencing parameter to reduce the impurities present in the gas. In the earlier days, in the down draft gasifiers, air was supplied through a central nozzle or nozzles with a ring [20]. These gasifiers are known as throated design down draft gasifier. Fuel flow was found to be a problem with the down draft type gasifier design with throat [21]. A down draft gasifier without throat was developed with multiple point of oxygen supply [22]. This report indicates that the throated designs were

Table 7 – Summary of electrical power output.

Time	Power output (kW_e)	Voltage (V)	Ampere (A)	Frequency (Hz)
1	69	393	101	46.9
2	69	398	104	47.0
3	69	394	105	46.9
4	71	393	105	46.8
5	69	397	103	46.8
6	70	399	100	47.0
7	69	399	100	47.0
8	70	409	93	50.1
9	70	401	97	47.0
10	69	399	97	47.0
11	70	399	97	47.0
12	69	409	99	46.7
13	70	401	99	46.7
14	70	399	99	47.3
15	68	410	94.0	46.6
16	67	388	95	53
17	69	408	101	53
18	68	409	101	47.4
19	68	407	98	52.9
20	69	404	101	47.1
21	65	400	98	52.5
22	70	409	102	52.5
23	70	409	101	53.6
24	66	410	97	52.3

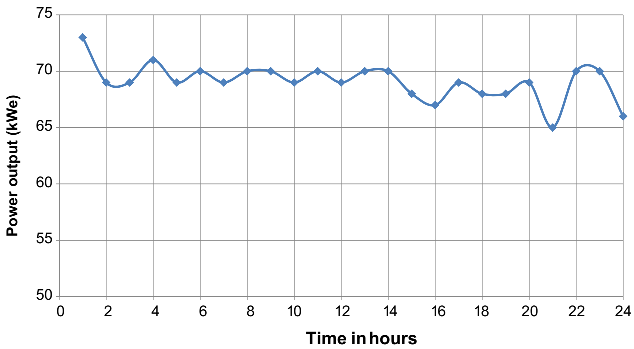

Fig. 6 – A profile of electrical power output.

Table 8 – Performance of the producer gas engine at various load conditions.

No.	Power output (kW_e)	Frequency (Hz)	Fuel wood consumption ($kg\ h^{-1}$)	Gas flow rate ($Nm^3\ h^{-1}$)	SFC ($kg\ kWh^{-1}$)
1	5	51.5	39.5	112	7.89
2	10	51.8	41.8	119	4.18
3	15	52.1	47.4	134	3.16
4	20	51.0	54.0	153	2.70
5	26	51.7	44.8	127	1.72
6	33	51.3	55.7	158	1.69
7	44	51.0	65.2	185	1.48
8	53	49.6	79.5	226	1.50
9	59	49.5	84.1	239	1.43
10	65	49.2	76.7	218	1.18
11	70	49.3	83.3	237	1.19
12	73	49.2	86.9	247	1.19

producing the gas with impurities less than 500 mg Nm^{-3}. In the early 70s, the gasifiers posed problems of gas quality; in particular, the problem was related to tar and particulate maters [17]. The tar content was having a large variation to the order of 2000 mg Nm^{-3} with the fuel moisture content in the range of 10–15% [17]. The tar content of the present system varies from 225 mg Nm^{-3} to 350 mg Nm^{-3}.

During 1987–1993 a national program was launched in India to promote gasifier system for power generations and irrigation pumping [23]. The systems installed during this period were used to operate diesel engines on dual fuel mode. Tar was projected as a major problem in gasifier operation. Various operational problems related to the fuel quality and gas quality were the learnings of the program. This indicates the operation and management problems are directly influenced by the status of the gasifier technology and the type of the gasification reactor.

The reactor design of the present gasifier was optimized for obtaining a good quality gas with low tar content. The gasifier reactor was modified with a focus on three key parameters to reduce the tar content in the raw gas itself (at the exit of the gasifier). The parameters considered for optimization of the gasification reactor performance are given below.

a. Optimizing the Specific Gasification Rate (SGR)
b. Optimizing the combination of the insulation layers
c. Optimizing the temperature of the air used for gasification.

The optimized gasification reactor was designed with a specific gasification rate (SGR) of 0.2 $Nm^3\ cm^2\ h^{-1}$. The reactor is provided with three layers of insulation. High alumina insulating refractory cast was used to insulate the reactor for minimizing the heat loss. The conductivity of the insulation materials is in the range of 8 W $m^{-1}\ K^{-1}$–15 W $m^{-1}\ K^{-1}$ at 1400 K. Preheated air at 250 °C was supplied to the reactor, to produce the gas with low impurities. The quality of the gas was found to be cleaner with the tar level lower than 350 mg Nm^{-3} (in raw gas).

In the process of optimizing the reactor design configurations, the Equivalence Ratio (ER) of the final reactor was found to be working at optimum level. (ER) influences the temperature of the reactor by controlling the combustion of biomass in the reactor. With a single layer insulation and a reactor temperature of 925 °C, the maximum hydrogen content of the gas was obtained when the ER is 0.35 [24]. This paper also reports that the temperature has continuously increased with increase in ER. In this present work, the ER is optimized with an appropriate insulation combination as shown in Fig. 3. Apart from reducing the heat loss from the reactor, ambient air was preheated and supplied at 250 °C to the reactor for maintaining the required temperature. Maintaining the reactor at high temperature enables to produce a good quality gas. The reactor temperature was measured as 935 °C near the nozzles and 1150 °C at the center of the reactor. The optimized reactor, to produce a cleaner gas was working with an ER of 0.35. With the ER of 0.35, the gasifier produces the gas with a calorific value of 5.7 MJ Nm^{-3}. An average calorific value of 5.5 MJ Nm^{-3} of gas is reported at the ER value of 0.35 [25]. Details of the

Table 9 – Reactor optimization and corresponding result of ER.

Variation in design and operating parameters			Input		Performance result				
SGR	Insulation layers	Air temperature (°C)	Fuel consumption rate ($kg\ h^{-1}$)	Air supply rate ($Nm^3\ h^{-1}$)	Gas production rate ($Nm^3\ h^{-1}$)	Reactor temperature (°C)	Tar content ($mg\ m^{-3}$)	ER	CV (MJ)
0.1	1	35	84	185	280	900	700	0.42	4.4
0.1	2	110	85	174	268	1020	628	0.39	4.9
0.2	3	260	87	160	255	1150	350	0.35	5.7

reactor optimization along with the result are presented in Table 9. The results are based on the operating condition of at full load for each reactor design. The performance of the optimized reactor with ER 0.35 at variable load conditions is provided in Table 8.

11.2. Analysis of the mass balance

The mass balance analysis was carried out as per Eqs. (1)–(7). The details of the mass flow analysis of input material and output products are presented in Table 10. A sankey diagram illustrating the mass balance of the system is presented in Fig. 7. The input material comprises 32% of fuel wood (1964 kg) and 68% of air (4151 kg) by mass fraction. This works out to be 2.11 kg of air was supplied for gasification 1.0 kg of fuel wood. This corresponds to an ER of 0.35. ER of 0.35 means, 35% of air is supplied in comparison with its stoichiometric air required for complete combustion. This is equivalent to the ER obtained in stoichiometric analysis reported by Rao et al. [10]. In the mass and energy balance analysis reported by Chern et al. [15], the ER is in the range of 0.21–0.29 which is on the lower side contributing towards a reduction in wood to gas ratio. A two-tier air supply down draft reactor is studied by Martinez et al. [11]. The calorific value of the gas is reported as 4.3 MJ Nm^{-3} with an ER at 0.4. It can be noticed that the calorific value is on the lower side due to higher ER. Increase in ER will lower the heat content of the gas with an increase in Nitrogen content. It can be concluded from the above discussions, that the lower is the ER; the higher is the charcoal production. In the present system with the ER of 0.35, the calorific value of the producer gas is 5.7 MJ Nm^{-3}. Hence, it may be concluded, that a gasification reactor produces the gas with higher calorific value at an optimized ER at 0.35.

The output product comprises producer gas, ash and fine particulates. In Fig. 7, it may be noted that 96.4% (mass fraction percentage) of the biomass fed into the gasifier was converted into producer gas. The biomass to gas conversion efficiency was 91.5% (Out of 84.5 kg of fuel wood 77.3 kg of wood is converted into gas), before improvements. An average of 92.3% of the biomass is converted into producer gas [26]. An increase in the biomass to gas conversation efficiency by 7.1% is observed when compared with the performance before the improvements made in the system. An increase in the biomass to gas conversation efficiency by 3% is observed when compared with Ref. [26]. Ash accumulation in the reactor can result into the continuous rise of dust content in the producer gas [27,28]. In the present system, an ash removal system with a vibrating grate was used to avoid the dust accumulation in the reactor.

The amount of charcoal and ash return of 3.5% is reported by Dasappa et al. [29] and 3 to 4% is reported by Chern et al. [15]. In the present gasifier, the charcoal and ash yield accounts only 0.5%. This is an 83% reduction in the charcoal return rate due to the improved design of the ash removal system. The unaccounted component of the mass balance analysis was 3%; this includes dust particles, which could not be captured in the mass balance analysis.

Table 10 – Summary of the mass flow analysis.

Cumulative hours	Input					Output	
	Wood consumption (kg)	Air flow velocity (m s^{-1})	Air flow (Nm^3)	Air flow (kg)	Wood + Air (kg)	Gas flow (Nm^3)	Gas flow (kg)
1	81	10.60	139	178	259	239	253
2	81	10.20	133	172	253	234	248
3	81	10.20	133	172	253	234	248
4	81	10.60	139	178	259	239	253
5	81	10.20	133	172	253	228	242
6	81	10.20	133	172	253	234	248
7	83	10.40	136	175	258	236	251
8	83	10.50	137	177	260	234	248
9	83	10.50	137	177	260	234	248
10	83	10.50	137	177	260	236	251
11	83	10.40	136	175	258	234	248
12	83	10.40	136	175	258	234	248
13	88	10.50	137	177	265	239	253
14	88	10.50	137	177	265	236	251
15	88	10.50	137	177	265	234	248
16	80	10.20	133	172	252	228	242
17	80	10.20	133	172	252	228	242
18	80	10.20	133	172	252	228	242
19	77	10.30	135	173	250	231	245
20	77	10.30	135	173	250	231	245
21	77	9.50	124	160	237	217	230
22	77	10.20	133	172	249	228	242
23	83	10.10	132	170	253	228	242
24	83	10.00	131	168	251	223	236

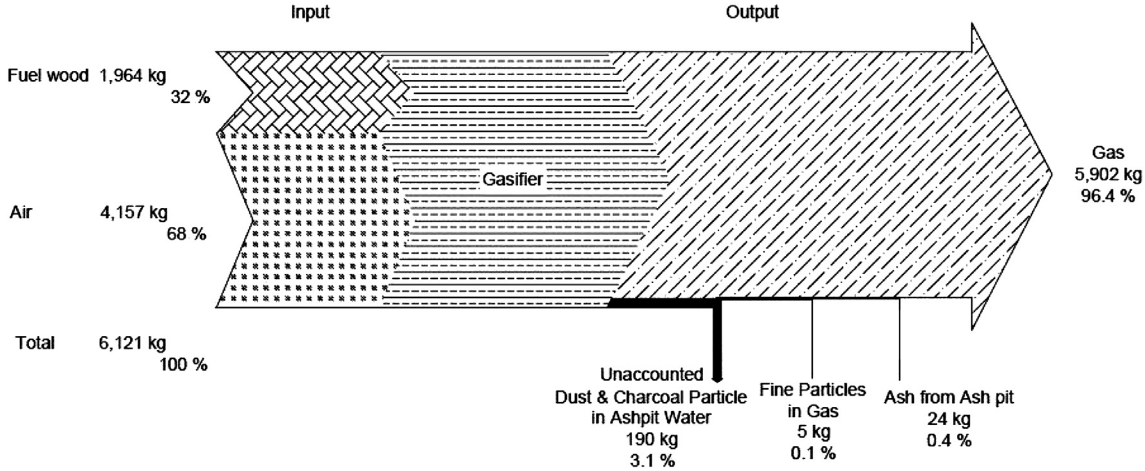

Fig. 7 – Mass balance analysis.

11.3. *Analysis of the energy balance*

The energy balance analysis was carried out by using Eqs. (8)–(14). A sankey diagram, showing the energy balance is presented in Fig. 8. From Fig. 8, it may be noted that 88.4% (energy fraction percentage) of the total energy content of the fuel wood is converted into producer gas. This is much higher than the reported value of around 69 ± 6% as reported in Refs. [10–12,14]. This is an increase of 21.4% of the cold gas efficiency in comparison with the system performance before improvements.

About 8.8% heat was carried away by the hot producer gas at the exit of the gasifier in the form of sensible heat. Out of this 3% of the heat is recycled into the gasifier, in the form of hot air. The remaining 5.8% of the heat energy was lost in the cooling and cleaning equipment. The unaccounted heat loss worked out to be 5.8%, which includes heat loss around the high temperature zones of the reactor and in the ash pit. Thus, the total energy lost in the process of converting the biomass into producer gas has found to be 11.6%. This is much less than the total heat loss of 20% reported in Refs. [9,12] and 30% reported in Ref. [11].

11.4. *Analysis of the elemental balance*

The elemental balance analysis was carried out, by using Eqs. (15)–(30). Elemental balance analysis is a complex process and could not be found any reported value on this subject. However, it is essential to carry out the elemental balance analysis to assess the performance of the reactor. The elemental balance also can be used for verification of the mass balance and the gas composition. A sankey diagram illustrating the elemental balance of the system is presented in Fig. 9. It may be noted From Fig. 9, that the nitrogen balance is accounted for 98.9% (3174 kg out of 3212 kg) of the input. The oxygen balance is accounted for 89.6% (1595 kg out of 1779 kg) of the input. Carbon balance is accounted for 99.4% (937 kg out of 943 kg) of the input. The Hydrogen element balance is accounted for 68.5% (124 kg out of 181 kg) of the input. The unaccounted component of the elemental analysis was 4.6%.

11.5. *Efficiency of the system*

The conversion efficiency of the biomass into producer gas was estimated using the Eq. (31). It has been observed that,

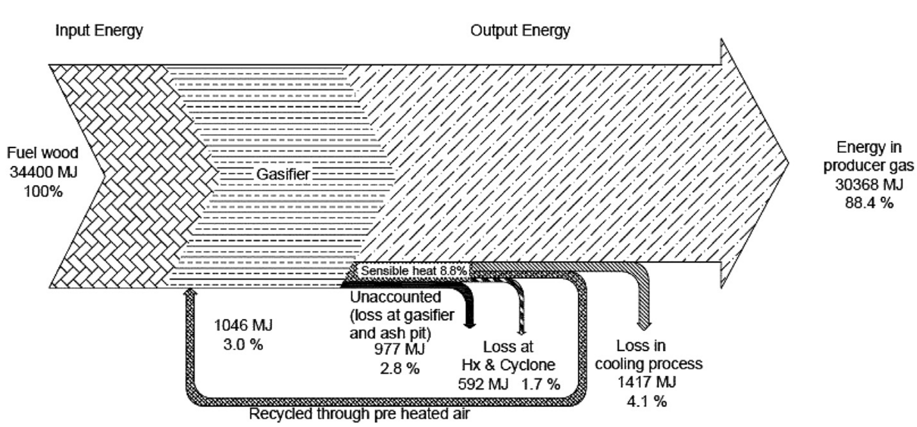

Fig. 8 – Energy balance analysis.

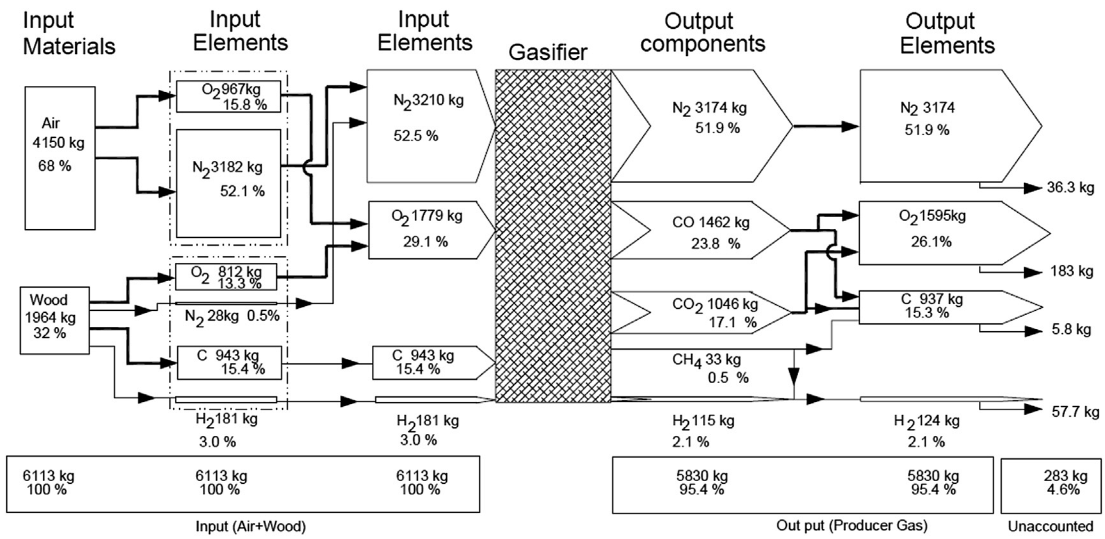

Fig. 9 – Elemental balance analysis.

1964 kg of biomass was converted into 5560 Nm^3 of producer gas. It means 34,400 MJ of energy from the fuel wood was converted into 30,368 MJ of energy in the form of producer gas. The energy conversion efficiency of biomass into producer gas was found to be 88.4%. This value is much higher than the reported value of the cold gas efficiency of 69 ± 6% [10–12,14].

In India, during 1980s and until the end of 1990s, IC engines are run with dual fuel supply [23,30]. Dual fuel engines were used for power generation using down draft gasifiers [22]. 1.1 kg of fuel wood is consumed for one hp of shaft power [31]. This works out to be a fuel consumption rate of 1.7 kg kWh^{-1} with 100% gas operated engine. Fuel consumption rate of 1.5 kg kWh^{-1} at 75% of diesel replacement and 2 kg kWh^{-1} at 100% producer gas was reported in Ref. [32]. Diesel engines were modified to run on 100% producer gas [33]. With 100% producer gas engine, the specific fuel consumption of 1.4 kg kWh^{-1} was observed in down draft gasifiers ranging from 15 to 35 kW_e capacity [34].

Table 11 – A summary of the parameters studied for estimating the efficiency of the system.

Hours	Wood consumption (kg)	Air flow ($Nm^3\ h^{-1}$)	Gas flow ($Nm^3\ h^{-1}$)	Engine (kW_e)	Air/Gas ratio	Gas/Wood ratio	Gasification η (%)	Wood to power η (%)	Gas to power η (%)	SFC (kg kWh^{-1})
1	81	139	239	73	0.58	2.94	0.89	0.19	0.22	1.11
2	81	133	234	69	0.57	2.87	0.87	0.18	0.21	1.18
3	81	133	234	69	0.57	2.87	0.87	0.18	0.21	1.18
4	81	139	239	71	0.58	2.94	0.89	0.19	0.21	1.15
5	81	133	228	69	0.58	2.81	0.85	0.18	0.22	1.18
6	81	133	234	70	0.57	2.87	0.87	0.19	0.21	1.16
7	83	136	236	69	0.57	2.85	0.86	0.18	0.21	1.20
8	83	137	234	70	0.59	2.82	0.85	0.18	0.21	1.19
9	83	137	234	70	0.59	2.82	0.85	0.18	0.21	1.19
10	83	137	236	69	0.58	2.85	0.86	0.18	0.21	1.20
11	83	136	234	70	0.58	2.82	0.85	0.18	0.21	1.18
12	83	136	234	69	0.58	2.82	0.85	0.18	0.21	1.20
13	88	137	239	70	0.57	2.70	0.82	0.17	0.21	1.26
14	88	137	236	70	0.58	2.68	0.81	0.17	0.21	1.26
15	88	137	234	68	0.59	2.65	0.80	0.17	0.21	1.30
16	80	133	228	67	0.58	2.86	0.87	0.18	0.21	1.19
17	80	133	228	69	0.58	2.86	0.87	0.19	0.22	1.16
18	80	133	228	68	0.58	2.86	0.87	0.18	0.21	1.17
19	77	135	231	68	0.58	3.00	0.91	0.19	0.21	1.13
20	77	135	231	69	0.58	3.00	0.91	0.19	0.21	1.12
21	77	124	217	65	0.57	2.82	0.86	0.18	0.21	1.18
22	77	133	228	70	0.58	2.97	0.90	0.20	0.22	1.10
23	83	132	228	70	0.58	2.75	0.84	0.18	0.22	1.18
24	83	131	223	66	0.59	2.69	0.82	0.17	0.21	1.26

The biomass to the electric power generation efficiency of the system was obtained by using Eq. (32). In the present system, 1964 kg of biomass was used to produce 1658 kWh of electricity, which works out to be SFC of 1.18 kg kWh^{-1}. This is much less than the SFC value reported in the studies [10,15]. This indicates a reduction of SFC of 19.7% was achieved, when comparing with the reported value of the SFC as 1.47 kg kWh^{-1}. Further, the present system's SFC of 1.18, is 9.2% lower in comparing with the SFC of 1.3 kg kWh^{-1} as reported in Refs. [10,15]. Biomass to electric power conversion efficiency of the system works out to be at 18%, when the SFC is 1.18 kg kWh^{-1}. The system was having an efficiency of 13.8%, before the design improvements are made. Hence, biomass to the electric power conversion efficiency of the system was increased by 4.2% due to the improvements in the reactor and ash removal system.

The producer gas to electric power generation efficiency of the system was estimated by using Eq. (33). The system used 5560 Nm^3 of producer gas to generate 1658 kWh of electricity this works out to be 3.35 Nm^3 kWh^{-1}. The energy conversion efficiency of the present system from producer gas to electric power is 21%. A summary of the parameters studied for estimating the efficiency of the system is presented in Table 11.

12. Conclusions

The biomass gasifier based power generation system was continuously operated and monitored during the experiment. The system was operated with a maximum load of 73 kW_e and a minimum load of 65 kW_e. With an ER of 0.35, the calorific value of the producer gas was 5.7 MJ Nm^{-3}. The charcoal return to the ash pit was reduced by 83% due to the improvement in the design of the ash removal system. The improved ash removal system and hot air injection contribute to minimize the specific fuel (wood) consumption to 1.18 kg kWh^{-1}. Three percent of the waste heat is recycled into the gasifier, in the form of hot air used for gasification. It was found that the waste heat recovery system used to provide hot air to the reactor, improves the gas quality and overall efficiency of the system. Biomass to electric power conversion efficiency is found to be 18%. The energy conversion efficiency of producer gas to electric power was worked out to be 21%. The electrical power output was remained closer to 73 kW_e, throughout the test run which indicates the reliability of the system. The mass balance analysis indicates that the biomass to gas conversion efficiency of the system is 96.8% (mass fraction percentage). The energy balance analysis indicates that 88.4% (energy fraction percentage) of the energy from the fuel wood was converted into producer gas.

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